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# Analyzing the current state and future development of carbon capture, utilization and storage (CCUS) strategies and technologies in China

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# Analyzing the current state and future development of carbon capture, utilization and storage (CCUS) strategies and technologies in China

**He Wang**[1,*]

[1]Dulwich College Beijing, Beijing, 100103, China

[*]Jo3y.w123@gmail.com

**Abstract.** Carbon capture, utilization, and storage (hereafter as CCUS) encompass the procedures of capturing carbon dioxide before it is emitted into the atmosphere, transporting it via pipelines or vehicles and finally utilizing it or storing it in a secure manner. CCUS is vital in transitioning the world into more sustainable and low carbon energy production since it serves as a temporary "band-aid" in reducing the impacts of humanity's high dependence on fossil fuels. The Chinese government has recently committed itself to reach carbon neutrality by 2060 and CCUS *technologies* will be a critical cornerstone in reaching this substantial goal. Up to 60% of China's energy supply in 2019 derived from coal, thus an effective CCUS strategy integrated with the 1,110 operational Chinese coal power plants could be decisive in reaching their carbon neutrality goal. This research paper will analyze the most effective best available technologies (BATs) in terms of cost efficiency and practicality, providing a comprehensive report on the optimal steps for China to take in order to reach its carbon neutral goals through CCUS.

**Keywords:** carbon capture, utilization and storage (CCUS), strategies and technologies

## 1. Introduction

Despite the growing consensus on utilizing more renewable energy sources, fossil fuels such as coal, oil and natural gases still make up around 80.9% of the global energy supply mix (26.8%, 30.9% and 23.2 % respectively in 2019) [1]. The combustion of these fossil fuels results in the release of greenhouse gases such as carbon dioxide into the atmosphere, causing anthropogenic heating of the globe. In light of these consequences, numerous more economically developed countries (hereafter as MEDCs) in Europe such as Germany, France and other Scandinavian countries have begun to switch predominantly to renewable energy sources, most notably Germany which plans on reaching 80% renewable energy usage by 2030 [2]. Nonetheless, this transition is expensive and suboptimal for poorer and newly developed countries that need to provide large amounts of energy for a growing population. Thus, many developing countries and even MEDCs continue to rely on fossil fuels as their primary energy source. As a result, anthropogenic climate change continues on a "current pledges" trajectory which predicts up to 3 degrees Celsius increases in global temperatures by 2100 [3]. In order to minimize the impacts of global fossil fuel reliance, there needs to be research into carbon management and the development of practical and cost-efficient ways to capture, store and utilize the carbon dioxide we emit into the atmosphere. Carbon management serves as a temporary yet vital step in transitioning the world into a carbon neutral society.

China plans on reaching this ambitious goal of carbon neutrality by 2060, and an effective CCUS strategy will be a pivotal factor in helping reach this target. Nonetheless, there are immense challenges which the Chinese government has to overcome in order to reach this goal. China is the largest carbon dioxide emitter, releasing 11.9 billion metric tons of $CO_2$ into the atmosphere in 2021 and accounting for 33% of the global total [4]. This is largely due to the fact that their energy mix is heavily fossil fuel reliant, with Coal, natural gas and oil accounting for 87.5% of their energy mix (61.1%, 7.3% and 19.1% respectively) [5]. China's coal reliance is supported by Figure 1, which shows the large number of active coal power plants in China as well as their locations. Consequently, this has caused immense adverse effects on public health in China. The economic and health ramifications of emissions are substantial, costing the economy 267 billion yuan a year, killing 1.1 million people prematurely per year and destroying 20 million metric tons of rice wheat maize and soybean [6]. These drastic consequences are driving factors for China's rigorous transition into renewable energy. However, China's decarbonization strategy has been halted post-COVID. Due to a slowing economy, the Chinese government has decided to favor a fossil fuel powered infrastructure stimulus, boosting coal production capacity by 300 million tons in 2021 [7]. Since China prioritizes economic growth over sustainable energy security, a full transition into renewable energy by 2060 can only occur if renewable energies can replace its existing energy requirements as well as the additional energy demand each year due to the push for economic growth [8]. As a result, large amounts of fossil fuel power plants will still operate during the transition into renewables, and a CCUS strategy will be needed to reduce the effects of which by as much as possible.

To reach the 2060 decarbonization goal, an estimated 1.82 billion metric tons of $CO_2$ emissions needs to be reduced each year [9]. Fortunately, implementing CCUS technology and strategies could reduce China's $CO_2$ emissions by 60 percent by 2050, but it will come with an estimated cost of 450 billion US dollars [9]. Hence, the Chinese government has not viewed it as a viable primary technology to aid in its 2060 goal, but rather an "alternative technology" [10]. Investors and policy makers have therefore regarded it as a high cost and risky endeavor to commit to its development. In the current economic climate where China is reconsidering its stance on coal power sources, it is crucial to address the negative connotations attached to CCUS strategies in China since it could be able to effectively reduce the negative effects of China's recent coal reliance. An extensive evaluation of CCUS's applicability in China will be explored throughout this report to discuss benefits, and drawbacks and address the different stakeholder group's possible concerns.

Currently, China only has 1 large scale operating CCUS project, being the CNPC Jilin project (refer to Figure 2) [11]. 5 additional CCUS projects are set to begin operations between late 2021 and 2022. The Chinese government has also released a roadmap for CCUS development, aiming for extensive industrial applications by 2030 as well as envisioning pipelines capable of transporting up to 2 million mt/year of $CO_2$ [12]. Nonetheless, China is yet to create specific regulations regarding carbon sequestration or provide any financial incentives for such projects. The International Energy Agency (hereafter as IEA) recommends the Chinese government to introduce a legal framework and provide incentives and subsidies to drive more interest in large scale CCUS operations [13,14,15]. Undoubtedly, China still requires further investment, research and development into CCUS to allow for its economic development to be sustainable. This research paper will evaluate the current state of CCUS technologies and propose the most effective future steps for China to take.

Carbon capture technologies are split into three distinct categories: precombustion, oxy-fuel combustion and post-combustion capture (PCC) [10]. Each carbon capture technology will be assessed for its effectiveness of usage in the Chinese context. This research paper will predominantly discuss the latter, being amine-based PCC technology, which is the most widespread in global CCUS operations and cost-effective.

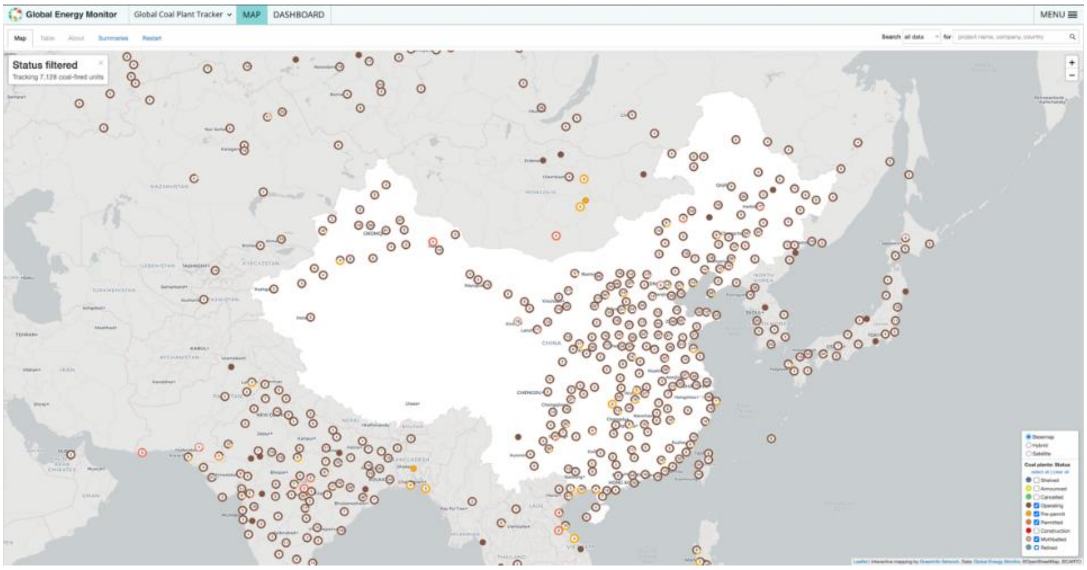


**Figure 1.** Coal plants currently operating in China (includes coal plants which are operating, permitted, pre-permitted and mothballed). [16].

| | NAME | SCALE Mt | OPERATION | INDUSTRY |
|---|---|---|---|---|
| 1 | CNPC Jilin Project | 0.6 | 2018 | Natural gas processing |
| 2 | CHNE Jingie | 0.1 | 2021 | Power generation |
| 3 | CNOOC Enping | 0.1 | 2021 | Natural gas processing |
| 4 | Sinopec Qilu Project | 0.4 | 2021 | Chemical production |
| 5 | Yanchang Integrated Project | 0.4 | 2021 | Chemical production |
| 6 | Sinopec Huadang Project | 0.5 | 2021 | Chemical production |
| 7 | CHNE Taizhou | 0.5 | 2025 | Power generation |
| 8 | China Northwest Hub | 1.5 | 2025 | Multiple |
| 9 | CRP Haifeng Project | 1.0 | 2030 | Power generation |
| 10 | Huaneng IGCC Project Phase III | 2.0 | 2030 | Power generation |
| 11 | Shenhua Ningxia Project | 2.0 | 2030 | Coal-to-liquids |
| 12 | Sinopec Shengli Project | 1.0 | 2030 | Power generation |
| 13 | CNPC Daqing | 3.0 | 2030 | Multiple |
| 14 | CNPC Changqing | 3.0 | 2030 | Multiple |
| 15 | CNPC Dagang | 1.0 | 2030 | Multiple |
| 16 | Shenzhen Energy | 0.5 | 2030 | Power generation |

**Figure 2.** Large scale operational and planned CCUS projects in China. [17].

## 2. Past and current status of CCUS development in China

Between 2006 to 2020, the interest of CCUS technologies in China has grown exponentially, with a cumulative 33 national policies issued during this time period [18]. Engagement surrounding CCUS in China could be split into 3 distinct time periods, being the 11th five-year period, 12th five-year period and the 13th five-year period (refer to Figure 3). In the 11th five-year period, the state council announced the "*Outline of National Medium- and Long-Term Science and Technology Development Program*" in 2006 where CCUS technologies are only briefly mentioned as a cutting-edge technology which can be considered in their long-term sustainability program, but no actions were taken to further develop it due to the technology being relatively unknown at that time. During the 12th five-year period, the number of policies regarding CCUS technologies increased drastically, most notably the *"12th Five-year National Special Plan for the Development of Carbon Capture, Utilization and Storage Technology"* which features 3 distinct sections.

The first section is a strategized plan for CCUS development, which identifies CCUS technologies as crucial for developing countries like China to generate energy in a low-carbon manner. The situation of CCUS technologies during the 12$^{th}$ five-year period was also evaluated, coming to the conclusion that the technology was still facing problems of high-cost operations and energy inefficiency and thus lacked long-term security. The second section is a CCUS roadmap created by the Ministry of Science and Technology of the Peoples Republic of China (hereafter as MOST). The roadmap aims to "provide technically viable and financially affordable technological options to combat climate change and facilitate socioeconomic sustainability". The roadmap prioritizes an extensive research phase until 2015, when the 12$^{th}$ five-year period ends. The last section is aimed at planning and promoting China's first CCUS pilot and demonstration projects. During this 12$^{th}$ five-year period, China had launched nine pilot projects and gained expertise through the process of launching them. However, these pilot projects were all small scaled, and the Chinese government were gradually preparing to take on larger scaled and higher $CO_2$ capacity CCUS projects (with large scale often referred to as projects with a $CO_2$ capacity of over 1 megaton). In the process of preparing for larger projects, China's National Development and Reform Commission (hereafter as NDRC) created policy frameworks to promote cross department collaboration to handle larger CCUS projects. The NDRC requested future CCUS projects to be fully integrated and involved in the six industries of thermal, coal, chemical, power, cement, and steel.

In the 13$^{th}$ five-year period, a number of policies created regarding CCUS had risen dramatically, with most of them focusing on project demonstration and steps to take in order to create large scale operational CCUS projects. A 13$^{th}$ five-year period roadmap was created with greater and more ambitious goals in mind (refer to Figure 4). This five-year period focused heavily on launching larger-scale operations, with the first close to large scale CCUS project in China being the CNPC Jilin facility which launched in 2018. This facility has a scale of 0.6 megatons, standing out from the various 0.1 megaton projects launched during this 13th five-year period.

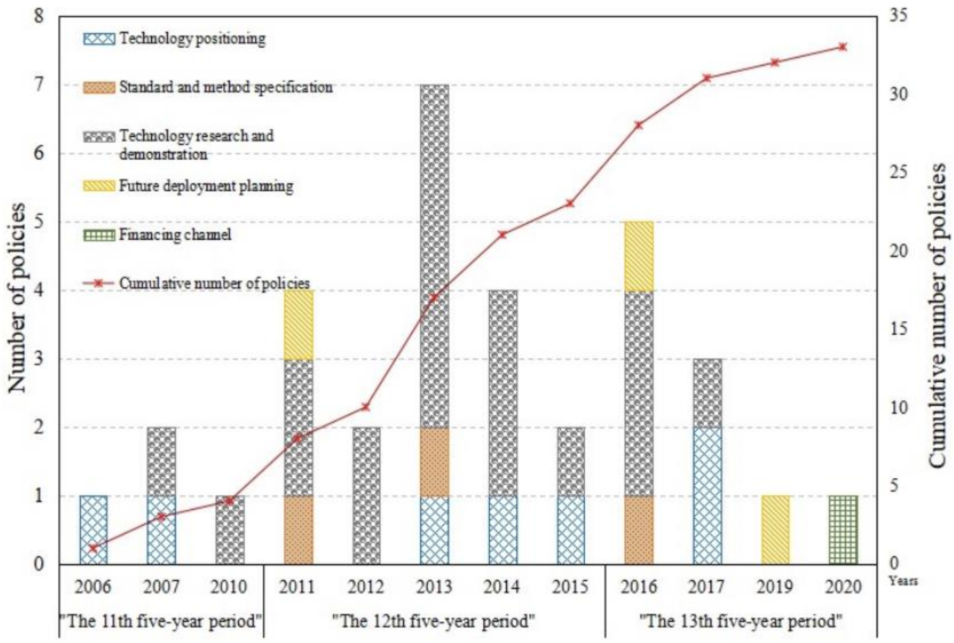


**Figure 3.** Graph visualizing the number of policies created across the 3 five year periods as well as which type of policy they were. [18].

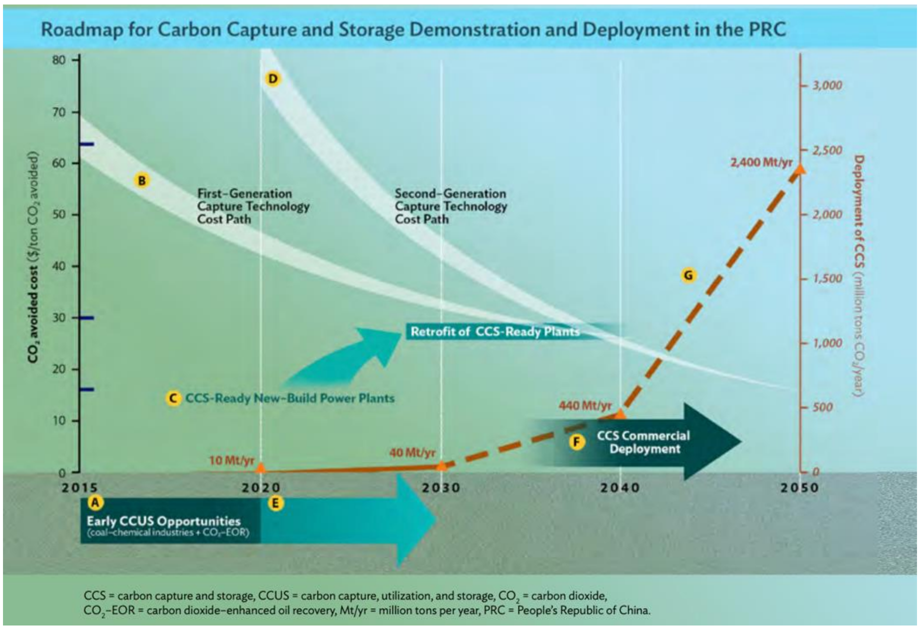


**Figure 4.** Roadmap for CCUS in China created by the Asia Development Bank [19].

## 3. Overview of CCUS Technologies

CCUS is a series of procedures which together create an effective carbon recycling system (refer to Figure 5). The system ensures that carbon from fossil fuel emissions is transported to and utilized in areas where it is needed rather than areas where it can cause harm, such as in the atmosphere. The system of Carbon capture and storage/sequestration (hereafter as CCS) has been around for a while, with the first CCS project proposed in 1938 and the first large scale project created in 1972 [20]. However, CCUS is a relatively new concept since it introduces the "utilization" step into the CCS system. CCUS is much more effective at reducing carbon footprint, since instead of simply storing carbon, it could be re-used in industries such as plastics, concrete or biofuel to name a few. This section will delve into the currently available technologies which carry out each step of the overall CCUS process, beginning with the first step which is capturing the carbon. The three main methods of capturing carbon in a CCUS system are: precombustion, oxy-fuel combustion and post-combustion.

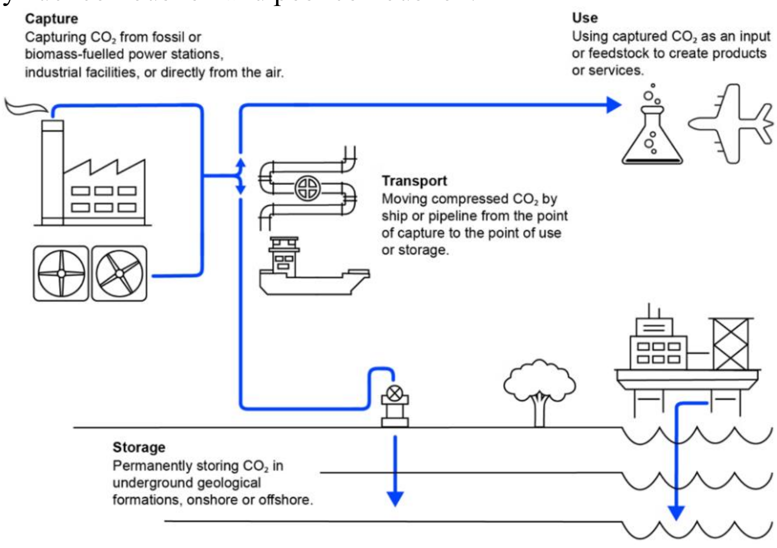


**Figure 5.** Visualization of how a typical CCUS system would operate, created by the International Energy Agency [21].

## 4. Pre-combustion carboncapture

Precombustion carbon capture refers to when $CO_2$ is removed from the fossil fuels prior to the combustion process. In precombustion, fossil fuels are heated in oxygen and steam ($H_2O$), also known as gasification, where fossil fuels are converted into gases. The amount of oxygen available in the gasifier is carefully controlled so that only a portion of the fuel is completely oxidized, providing the necessary heat to chemically decompose the compounds of the fuel and create a mixture of gases made up of hydrogen ($H_2$) and carbon monoxide (CO). This mixture of gases is known as the synthesis gas (hereafter as syngas). The syngas then undergoes a water-gas shift reaction (hereafter as WGSR), which converts carbon monoxide to carbon dioxide and increases the mole concentrations of $H_2$ and $CO_2$ to around 55% and 40% respectively [22]. The purpose of WGSR is to adjust the hydrogen/carbon monoxide (hereafter as $H_2$/CO) ratio. WGSR is a reversible reaction with the formula:

$$CO + H_2O \rightleftharpoons H_2 + CO_2 \qquad \Delta H° = -41 \text{ kJ/mol}$$

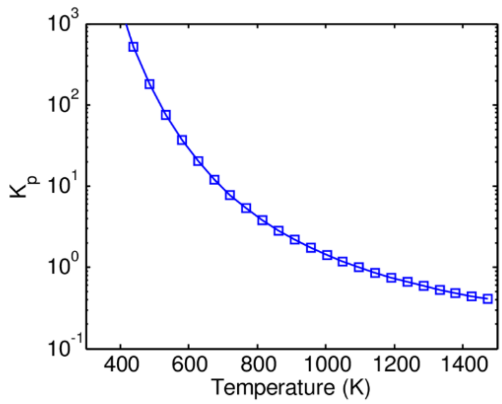


**Figure 6.** Equilibrium constant against temperature (Kelvin) for WGSR [23].

The resulting syngas from gasification is usually around 600 and 700 °C, requiring time to cool down before going through WGSR. Since WGSR is an exothermic reaction, a lower temperature would generate a higher equilibrium constant (as seen in Figure6) and thus would favor the creation of products and reach a higher $H_2$/CO ratio. There are two types of WGSR, being sweet shift/clean shift and sour shift. A sweet shift is when the WGSR takes place after sulfur and other impurities are removed from the syngas whilst a sour shift is when the WGSR takes place before sulfur and other impurities are removed. A sweet shift is not typically suitable for coal gasification applications since the most sulfur that can be removed through a “coal cleaning” process is a 30% reduction. On the other hand, scrubbers are incredibly effective at removing sulfur with up to 98% efficacy. Nonetheless, scrubbers are only applicable to post-combustion processes. A sour shift requires temperatures of around 250-500 °C and can tolerate up to 1000 ppm of sulfur content in the syngas (refer to Figure 7). A cobalt-molybdenum sulfide catalyst (or CoMoS) is used in a sour shift reaction. After the WGSR, the shifted syngas contains $CO_2$ at higher amounts and high pressure, which improves the driving forces for $CO_2$ separation techniques. As a result, pre-combustion carbon capture (typically ~50% carbon concentration) removes carbon when it is at a higher concentration and pressure than in post-combustion carbon capture (typically 5-15% carbon concentration), making it much more efficient.

Nonetheless, the costs of today’s commercially available pre-combustion carbon capture technologies are significantly higher than post-combustion, costing around 135 USD/MWh to capture $CO_2$ (see Table 2). Additionally, efficiency in pre-combustion carbon capture can be improved if cheaper and more efficient “coal cleaning” processes can be introduced, which will allow for the syngas to undergo a low-temperature sweet shift, where a better $H_2$/CO ratio can be achieved. Pre-combustion carbon capture can be utilized in an Integrated Coal Gasification Combined Cycle (hereafter as IGCC) power plant, where gasification is a necessary process for fossil fuels to undergo to generate power. Figure 8 shows how a typical IGCC power plant would operate. An example of an IGCC power plant which utilizes pre-combustion carbon capture in China is the Huaneng Tianjin IGCC plant, currently reducing $CO_2$ emissions by 372,000 metric tons per year [24].

- High-temperature shift (HTS) catalysts
  Active component: $Fe_3O_4$ with $Cr_2O_3$ as stabiliser
  Operating conditions: 350 – 500 °C; sulphur content syngas < 20 ppm[1]
- Low-temperature shift (LTS) catalysts
  Active component: Cu supported by ZnO and $Al_2O_3$
  Operating conditions[2]: 185 – 275 °C; sulphur content syngas < 0.1 ppm
- Sour shift catalysts
  Active component: Sulphided Co and Mo (CoMoS)
  Operating conditions: 250 – 500 °C; sulphur content syngas > 1000 ppm[3]

**Figure 7.** Types of WGSR and their reaction conditions and catalysts [25].

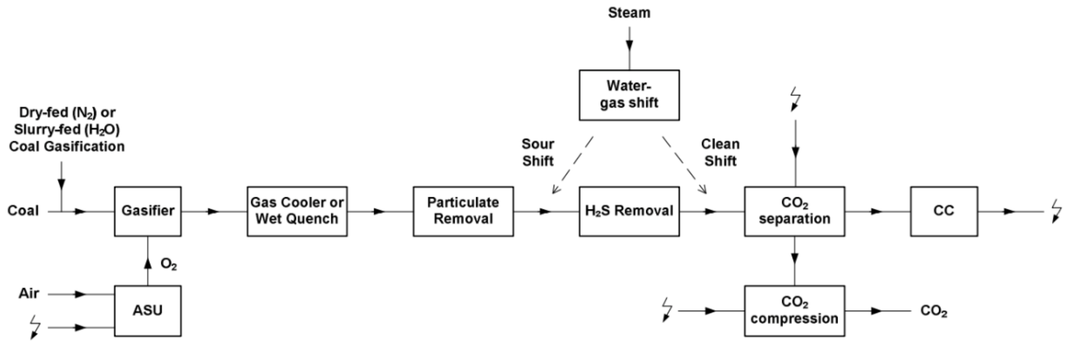


**Figure 8.** Flow diagram for a typical IGCC power plant with pre-combustion carbon capture [26].

## 5. Oxy-fuel combustion carbon capture

Oxy-fuel combustion is the burning of fossil fuels in approximately pure oxygen or a mixture of oxygen and recycled flue gas rather than air. Figure 9 shows how a typical oxy-fuel combustion plant would operate. The input air is processed through an air separation unit (ASU) so that much of the nitrogen content is removed, leaving a mixture containing up to 95% oxygen [27]. ASU predominantly utilizes cryogenic distillation, a fractional distillation process which separates nitrogen from oxygen and a small amount of argon. The gas stream of high oxygen purity is fired with the fossil fuels, creating a resulting gas mixture of high $CO_2$ concentration. High oxygen purity combustion allows for higher flame temperatures and intensities (as seen in Fig 10), as well as a 75% lower flue gas yield (in terms of mass and volume) compared to traditional air-fired combustion [28]. This all allows for the flue gas to be $CO_2$-rich and highly concentrated, making compression and sequestration much simpler.

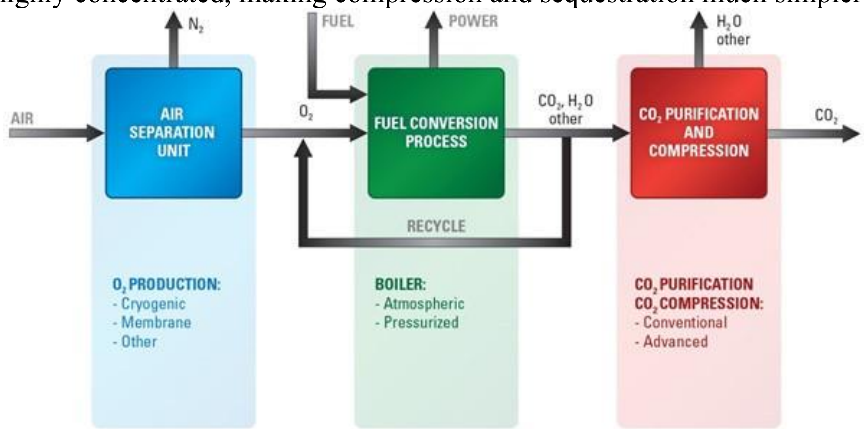


**Figure 9.** Flow diagram for an oxy-fuel combustion carbon capture system [28].

Nonetheless, oxy-fuel combustion is still relatively new, with large amounts of research and development efforts needed to better understand oxy-fuel combustion at high temperatures and pressure.

Additionally, a large contributor to the high costs of oxy-fuel combustion is the process of oxygen separation from air. This separation process requires large amounts of energy, with a large ASU consuming up to 100 MW of electricity which is approximately the capacity of a small power plant [29]. Thus, this process faces two major areas of improvement which is the need to reduce the cost of a pure oxygen supply and increasing the overall system efficiency. China currently has one oxy-fuel plant which is located in Yin Cheng, Hubei province. The plant is operated by the Huazhong University of Science and Technology (hereafter as HUST) and has carried out oxy-fuel combustion projects of 0.3 MW and 3MW in size, which are comparably low compared to the operating energy requirements. HUST has created a future roadmap for oxy-fuel development, with energy capacities evolving from 0.3 MW to 3MW, 35MW, 200MW and finally 600MW [30].

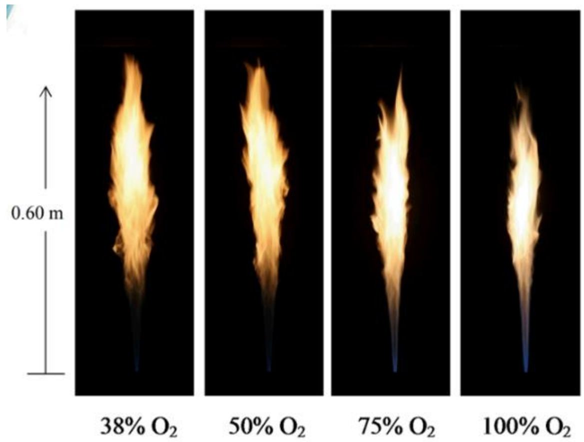


**Figure 10.** Varying flame intensity based on oxygen purity [31].

## 6. Post-combustion carbon capture

Post-combustion carbon capture is the separation of $CO_2$ from flue gases (a mixture of $CO_2$, water vapor, nitrogen, and sulfur dioxide) after the combustion process. Post-combustion carbon capture (hereafter as PCC) is the most commonly used and widespread carbon capture method since it can be deployed in pre-existing coal fired power plants by installing technologies at the end of the power generating process rather than integrating technologies into the process. With oxy-fuel combustion or pre-combustion carbon capture, processes need to be installed into the power generating procedure for effective carbon capture (e.g., gasifiers and ASU), whilst PCC works as an add on to existing power plants (known as retrofitting).

PCC typically utilizes an absorption-desorption operation, where sour gas/acidic gas (gas with high $CO_2$ or $H_2S$ content) is absorbed by an aqueous amine solution, becoming “amine rich” and transported to another column where $CO_2$ or $H_2S$ is then desorbed from the amine solution and transported elsewhere. This treatment of gas is also known as sweetening sour gas. Figure 11 shows how a typical absorption-desorption process would operate in PCC. The most commonly used amine solutions are Diethanolamine (DEA) and Monoethanolamine (MEA), with a variety of other amine solutions available each with their distinct advantages and disadvantages. Table 3 shows the $CO_2$ absorption capacities of DEA, MEA and Triethylamine (TEA).

**Table 1.** 11 Cfig$O_2$ absorption capacity for different types of amines [32].

| | Monoethanolamine: | Diethanolamine: | Triethylamine: |
|---|---|---|---|
| $CO_2$ absorption capacity: | 0.5180 mol $CO_2$/mol amine | 0.5903 mol $CO_2$/mol amine | 0.2608 mol $CO_2$/mol amine |

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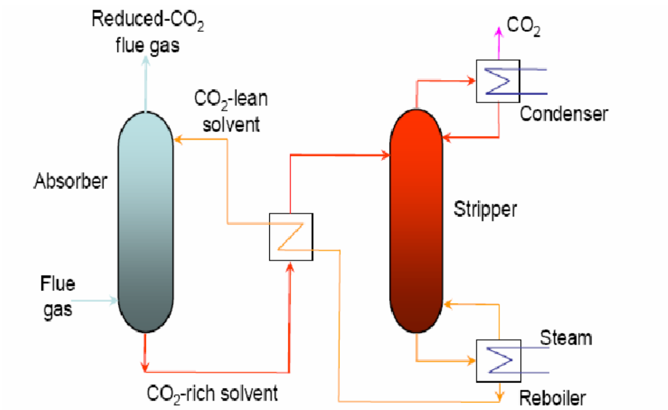


**Figure 11.** Diagram of the amine absorption process in PCC [33].

The reaction between amines and aqueous $CO_2$ is an acid-base reaction. Figure 12 shows the reaction diagram of the two compounds. All amines are basic since the nitrogen in their structures each contains a lone pair. This lone pair reacts with the $CO_2$ in the flue gas (which contains some steam), creating carbonic acid. The overall reaction of the absorption of $CO_2$ by amine is:

$$2NRH_2 + H_2O + CO_2 \longrightarrow 2NRH_3^+ + HCO_3^{2-}$$

The resulting solvent, now rich in $CO_2$ is heated to approximately 105 °C to remove the $CO_2$, leaving behind the amine solution which will absorb $CO_2$ again. The maximum absorption of $CO_2$ in this reaction occurs when the majority of $CO_2$ absorbed creates a bicarbonate salt, however, when using an MEA amine, the majority of salt created at equilibrium is a carbamate, thus limiting the $CO_2$ absorption capacity to around 0.5 moles of $CO_2$ per mole of MEA [34].

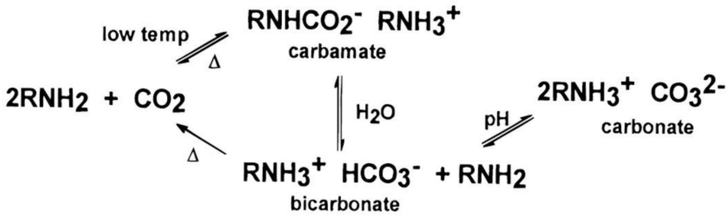


**Figure 12.** Reaction diagram of amines with aqueous $CO_2$ [34].

Despite the ease of installation compared to the other two methods of carbon capture, PCC faces numerous issues. The $CO_2$ present in flue gas post-combustion is at low concentration, typically around 13 to 15 percent for pulverized coal-fired plants (hereafter as PC) and 3 to 4 percent for natural gas-fired plants [35]. Thus, a large volume of gas needs to be processed. Moreover, there could be impurities such as sulfur dioxide, nitrogen oxide and particulate matter which can damage the sorbents utilized in carbon capture, degrading the effectiveness of the process. MEA and DEA also require large amounts of energy to absorb and strip $CO_2$ and can take up to 70% of total operating costs [36]. Amines are also corrosive, so the materials chosen for amine-based PCC operations need to be chosen carefully.

## 7. Evaluation of main carbon capture technologies

The three main carbon capture technologies each have their advantages and disadvantages (see Figure 13). Carbon is the hardest to sequester in PCC, since the flue gas is at a much lower pressure compared to Pre-combustion and Oxyfuel combustion. However, PCC can be retrofitted, whereas Pre-combustion and oxyfuel combustion cannot. PCC is also the cheapest carbon capture solution (see Table.2) out of the three. Pre-combustion captures carbon at a higher $CO_2$ concentration than PCC but lower than Oxy-fuel. Although they cannot be retrofitted, if the power plant is built with precombustion in mind, it is significantly more efficient and cost-effective to operate than PCC. The WGSR of the syngas can also produce hydrogen fuel, which can be sold for use. Nonetheless, Pre-combustion is the most expensive carbon capture technology out of the three. Oxyfuel combustion captures carbon at the highest $CO_2$ concentration compared to the other technologies. However, it is a relatively new technology with no experience with large scale applications. Startup costs are also expensive mainly due to the hefty price of cryogenic distillation units.

| Post-combustion | Pre-combustion | Oxyfuel combustion |
|---|---|---|
| • Applicable to the majority of existing coal-fired plants<br>• Low $CO_2$ partial pressure<br>• Significantly higher performance or circulation volume is required for high capture levels<br>• $CO_2$ produced at low pressure compared to sequestration requirements.<br>• Retrofit technology option<br>• Improved solvents may reduce energy losses.<br>• Significant cost savings are possible. | • Generally higher $CO_2$ concentration than for pos-combustion capture<br>• Higher driving force for $CO_2$ separation<br>• Fuel processing is needed<br>• Potential for reduction in compression costs/loads<br>• For coal plants, efficiency and cost penalties are generally lower than for post-combustion capture<br>• Barriers to commercial application of gasification are common in pre-combustion capture<br>• Extensive supporting systems requirements | • Very high $CO_2$ concentration in flue gas<br>• Combustors would be fairly conventional<br>• Large cryogenic oxygen production requirement may be cost prohibitive<br>• Large cryogenic oxygen production requirement maybe cost prohibitive<br>• Need to recycle large quantities of flue gas to avoid excessively high combustion temperatures<br>• $CO_2$ is recycled to the compressor to provide the expansion medium, instead of air<br>• Novel turbine cycles have been proposed, which eliminate shift reaction/fuel gas $CO_2$ separation<br>• Potential for advanced oxygen separation membranes with lower energy consumption<br>• Decreased process efficiency |

**Figure 13.** Advantages and Disadvantages of the three main Carbon Capture technologies. [37].

**Table 2.** Average cost of the three main Carbon Capture technologies in China in 2017 [38].

| | Pre-combustion (IGCC) carbon capture: | Post-combustion carbon capture: | Oxy-fuel combustion carbon capture: |
|---|---|---|---|
| Price per MWh | ~135 USD | ~120 USD | ~125USD |

## 8. Direct air capture (DAC)

Direct air capture (hereafter as DAC) refers to when $CO_2$ is directly extracted from the atmosphere. Currently, DAC technologies can be split into two categories: liquid and solid DAC. Figure 14 shows how a typical liquid (solvent) DAC system would operate. In liquid DAC, an air contactor draws in atmospheric air (known as ambient air) through a fan. The air contactor then reacts the ambient air containing $CO_2$ with an aqueous potassium hydroxide solution (KOH) to create water and potassium carbonate ($K_2CO_3$).

$$2KOH + CO_2 \longrightarrow H_2O + K_2CO_3$$

Ambient air typically enters the air contactor at 0.04% $CO_2$ composition and leaves with 75% $CO_2$ in potassium carbonate form. The aqueous potassium carbonate is then transported into a causticizer and reacted with calcium hydroxide ($Ca(OH)_2$), creating calcium carbonate ($CaCO_3$) and potassium hydroxide (KOH). The KOH solvent can then be reused in the air contactor to capture more $CO_2$.

$$K_2CO_3 + H_2O + Ca(OH)_2 \longrightarrow CaCO_3 + 2KOH$$

The calcium carbonate created then undergoes a clarification and filter process where it is purified, and water is separated. The resulting purified calcium carbonate is fed into the calciner where it is heated to high temperatures (around 900 °C), separating it into calcium oxide and highly concentrated $CO_2$.

$$CaCO_3 \longrightarrow CaO + CO_2$$

Calcium oxide is transported to the slaker, where it reacts with water to create calcium hydroxide ($Ca(OH)_2$) and reused in the causticizer. The high concentration and purity $CO_2$ are then compressed and transported elsewhere for either sequestration or utilization.

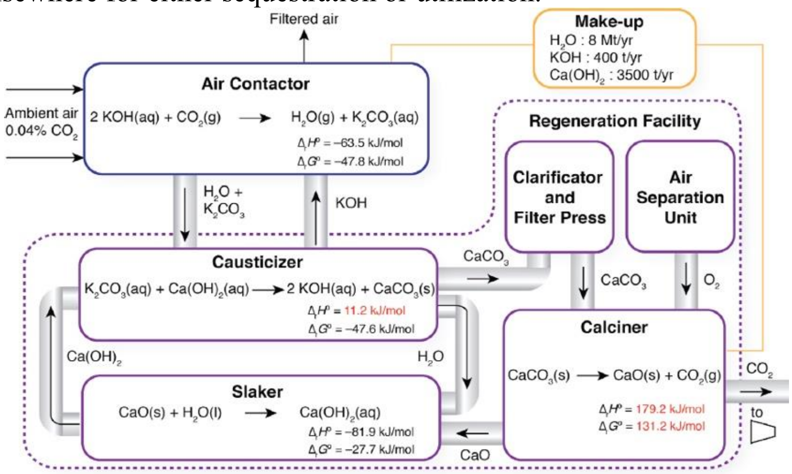


**Figure 14.** Flow diagram of a typical solvent-based direct air capture system [39].

In solid DAC, the process is relatively similar to post-combustion carbon capture where the $CO_2$ is absorbed with a sorbent and then heated to be desorbed, producing a concentrated $CO_2$ stream. Instead of the amine gas treatment typically used in post-combustion carbon capture, Solid DAC utilizes solid sorbents such as mesoporous silicas, zeolites and carbonates.

## 9. Carbon utilization

Up to 40 million metric tons of $CO_2$ is captured per year worldwide [40] and it can be utilized in a plethora of applications, with the most common being enhanced oil recovery (hereafter as EOR). Crude oil extraction can be split into the three phases of primary, secondary, and tertiary (enhanced) recovery. Primary recovery typically involves pumps and other artificial lifting techniques to deliver oil from underground to the surface. This technique only yields around 10% of the reservoir's oil [41]. Secondary recovery involves injecting water or gas to displace the oil which extracts a higher yield of around 20 to 40% [41]. Tertiary/enhanced recovery can be split into three categories, being thermal recovery, chemical injection, and gas injection, with $CO_2$ EOR being the latter. $CO_2$ captured from power plants through carbon capture is injected at high pressure back into the oil reservoir, cracking subsurface rocks and expanding the reservoir. Some gases can also dissolve in the oil, lowering its viscosity and improving its flow, allowing for easier recovery. EOR techniques can extract around 30 to 60 % of the reservoir's oil [41]. 34 EOR projects have been conducted in China (see Figure 15), accounting for 18% of China's total oil production in 2016 [42].

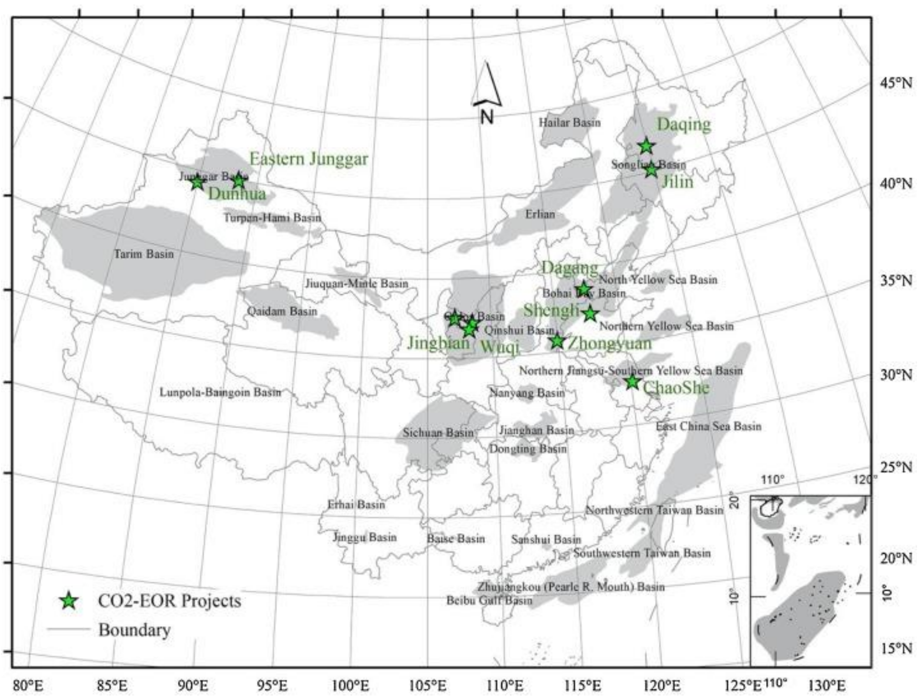


**Figure 15.** Map of $CO_2$ enhanced oil recovery projects in China [42].

Whilst there are other methods of utilizing $CO_2$ aside from EOR, most are in R&D phase with only a select few which have reached commercially available status. Nonetheless, there are promising applications of $CO_2$ which have been tested. This section will overview innovative ways of using $CO_2$ as well as several companies and start-ups which have begun implementing them.

$CO_2$ is utilized is in building materials, most notably cement. Terra $CO_2$, a company in Canada, utilizes $CO_2$ by reacting it with silicate rocks (e.g., metal sulfides, a byproduct of mining) to create a cement replacement. For every ton of Terra $CO_2$ product used instead of traditional cement, a 70% reduction in $CO_2$ emissions is achieved [43]. Carbon upcycling is another company which utilizes carbon by infusing fly ash and slag (byproducts of coal incineration plants) into cement. This method can achieve up to 30% reduction in $CO_2$ compared to traditional methods [43].

Twelve, a company based in Berkeley, California, has created their $CO_2$-made material from captured $CO_2$. The company's technology, Opus, mimics photosynthesis on an industrial scale to create carbon-based materials. The company has already partnered with Mercedes-Benz to create $CO_2$-made car parts, tide with $CO_2$made detergent ingredients and pangaia with $CO_2$-made lenses.

$CO_2$ is utilized is in the creation of calcium carbonate. An example would be seabound, a UK based company which has developed an on-board carbon capture system for ships. $CO_2$ emissions are bubbled through lime (CaO) pebbles, reacting to form calcium carbonate ($CaCO_3$). Yuanchu technology, a company in China, is capturing carbon and sequestering it by creating calcium carbonate. The company currently has a pilot project in Datong city, China as well as two future projects each capable of capturing 200,000 tons of $CO_2$/year [44]. The calcium carbonate created can have numerous uses, including calcium supplements, pH control for plants, paint coatings and heartburn treatment to name a few.

## 10. Future steps for CCUS development in China

Words such as "large scale" and "commercially operating" are often used when describing the state of CCUS in China. In the past, China has proven to show expertise and have sufficient capability in operating CCUS projects, as shown through their project demonstrations. Nonetheless, they are small scaled and do not demonstrate strong feasibility in terms of economies of scale for whole chain deployment. Thus, the current $14^{th}$ five-year period serves as a decisive period of time for China to truly integrate CCUS systems into their carbon neutrality strategy. With less than a decade of time left, China plans on reaching its carbon peak by 2030. China needs to focus on transitioning from the research and development phase of CCUS to constructing them. To achieve this, China needs to focus on four areas of development, being advocacy, policies, and driving innovation for CCUS.

Advocacy is an important factor in reaching carbon neutral goals, since (as previously mentioned) there is a lack of knowledge on the potential of CCUS technologies. The Chinese government view it as an "alternative technology" whilst investors also regard it as a technology which operates on losses. Despite CCUS's numerous advantages, skepticism on it is not unfounded, with much of the CCUS demonstrations operating on both economical and energy losses. Nonetheless, advocacy for CCUS is rising both in China and internationally. Elon Musk announced a 100 million USD incentive in 2021 for effective CCUS and carbon removal technologies, reigniting interest in this field. China currently has two projects which entered the top 60 of the competition and 21 total registered projects [44]. There has also been recent interest from China's major energy providers in CCUS, these include Sinopec, China National Petroleum Corporation (CNPC) and China National Offshore Oil Corporation (CNOOC). Together they operate 8 CCUS projects with a combined capacity of 2.9 million mt/year since September 2021, making up 72% of China's total capacity [45].

Policies also serve an important role in driving China's future CCUS development. The government has already requested Sinopec, CNPC and CNOOC to reduce $CO_2$ emissions by 18% by 2025. This policy may likely have provoked Sinopec to commission its 1 million mt/year CCUS project at its Qilu Facility in Shandong. Further incentivizing policies are still required to ensure CCUS is adopted widely throughout China. The Asia Investor Group on Climate Change estimated that the cost of generating electricity through coal-powered carbon capture is at 110 USD/MWh, significantly higher than that of solar or wind [45]. Further incentives are required to speed up the adoption of CCUS in China, creating higher economies of scale and lowering the costs of operations.

As China's economies and industries continue growing, an increasingly larger amount of $CO_2$ emissions needs to be reduced, thus greater development and innovation in CCUS are required to meet this demand. Shell China estimates that in order for China to reach its carbon neutral goals by 2060, it needs to increase its CCUS capacity by 400 times the amount it currently is standing at [46]. Industries also continue to consume energy at a greater rate (see Table 1), and thus innovative solutions are crucial for China's CCUS development at this stage. Greater investment into research and development is required to decrease CCUS operational costs to a degree where it can meet up with the constantly growing standards.

**Table 3.** Demand for Carbon reduction through CCUS by industry in China [47].

| | | | | Unit: 100 million tons per year | | |
|---|---|---|---|---|---|---|
| Industry | 2025 | 2030 | 2035 | 2040 | 2050 | 2060 |
| Coal power generation | 0.06 | 0.2 | 0.5-1 | 2-5 | 2-5 | 2-5 |
| steel | 0.01 | 0.02-0.05 | 0.1-0.2 | 0.2-0.3 | 0.5-0.7 | 0.9-1.1 |
| Petrochemical/chemical | 0.05 | 0.5 | 0.3 | 0 | 0 | 0 |
| All industries | 0.09-0.3 | 0.2-4.08 | 1.19-8.5 | 3.7-13 | 6-14.5 | 10-18.2 |

## 11. Conclusion

This paper analyses the state of CCUS through a holistic review of both political and technological factors. CCUS is a vital technology in the effort to mitigate the effects of anthropogenic climate change. It serves as a temporary band aid for humanity's fossil fuel usage as it eventually adopts renewable energy. Moreover, CCUS technology can significantly reduce China's $CO_2$ usage, working in sync with China's 2060 zero carbon goal.

Throughout the $11^{th}$ to $14^{th}$ five-year periods, CCUS has grown from a "considered technology" to an indispensable aspect of China's decarbonization goals. Large pilot projects such as the Jilin CNPC facility and numerous other future projects are working towards the megaton milestone so that CCUS can become a large scale and commercially operating technology in China.

The three main carbon capture technologies of PCC, pre-combustion, and oxy-fuel combustion each have their own respective pilot projects in China. Nonetheless, PCC has been the most prominent and widespread due to its retrofitting capabilities. China has invested heavily in ensuring CCUS becomes more widespread, as well as stressed the importance of R&D of CCUS technologies.

Supporting innovative start-ups is the correct direction China should take in order to promote CCUS and reach its 2060 decarbonization goals. Currently, the most common usage of captured carbon in China is through EOR, which only promotes more fossil fuel usage. Investing in innovative CCUS systems such as utilizing $CO_2$ in cement, limestone and carbon-based materials can create groundbreaking progress.

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